

Drifter Motion Planning for Optimal Surveillance of the Ocean (DRIMPOS)

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LONG-TERM GOALS

In recent years substantial progress, much of it resulting directly from ONR funding initiatives, has been made in understanding fundamental features of transport and mixing in oceans using methods derived from dynamical systems theory. The purpose of the current collaborative research is to extend these methods to the design of control algorithms for Drifter Motion Planning for Optimal Surveillance of the Ocean (DRIMPOS). This effort is a direct attempt to transition Lagrangian based dynamical systems methods from diagnostic, postdictive tools to essential and active components in the design of oceanographic and naval observing systems. The specific goals of the research project include the development of flow-based control algorithms for drifting autonomous sensing systems.

OBJECTIVES

Couple dynamical systems ideas and control-theoretic algorithms to produce real-time control of gliders based on the output from high resolution coastal ocean model forecasting systems. Specifically, use knowledge of Lagrangian ocean dynamics to develop readily computable, optimal control algorithms to (1) maximize the loitering time of autonomous surveillance platforms in a prescribed region under energy constraints (2) optimize sensor coverage of a given surveillance region by single or multiple platforms.

APPROACH

Work completed under this grant involves close collaboration with Igor Mezic at the University of California Santa Barbara. Non-linear optimal control theoretic ideas formulated by the UCSB group have been adapted for implementation in the highly inhomogeneous, time-dependent flow fields produced by high-resolution ocean prediction models. For illustrative purposes we consider 1km resolution, data-assimilating hind-casts of the Adriatic Sea from the Naval Coastal Ocean Model (NCOM) provided by Paul Martin at NRL-Stennis. An extremal field algorithm, originally proposed in the context of time-independent input velocity fields, is extended to non-autonomous inputs to solve Zermelo's minimum time navigation problem efficiently. The result, for a given input ocean velocity field, is the optimal feedback controller for an idealized autonomous vehicle along with the associated optimal cost function.

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WORK COMPLETED

- 1) Developed Optimal Control framework for localization of idealized autonomous underwater vehicles within a pre-defined box. The main achievement here was localization times that exceed by up to an order of magnitude (e.g. 10 days vs. 1 day) those achievable without optimal control, or even with central, open-loop control (see Figure 4). The optimal control framework was applied to a realistic 2-D, NRL Stennis-developed, numerical model - NCOM

RESULTS

Optimal Control

We have successfully applied nonlinear optimal control methods to the problem of maneuvering a drifter in a coastal ocean flow given by a numerically defined vector field of surface currents produced from a realistic ocean model. We consider the problem of maximizing the loitering time of an AUV in a 44 X 44 km square of ocean here defined to be an arbitrarily chosen, near coastal region of the eastern Adriatic Sea as shown in Figure 1. Temporal resolution is hourly for a 30 day period. Linear and cubic interpolation schemes were used to approximate the dynamics at interior points in simulating the motion of a particle over subsets of the 30 day time frame, whether with or without control.

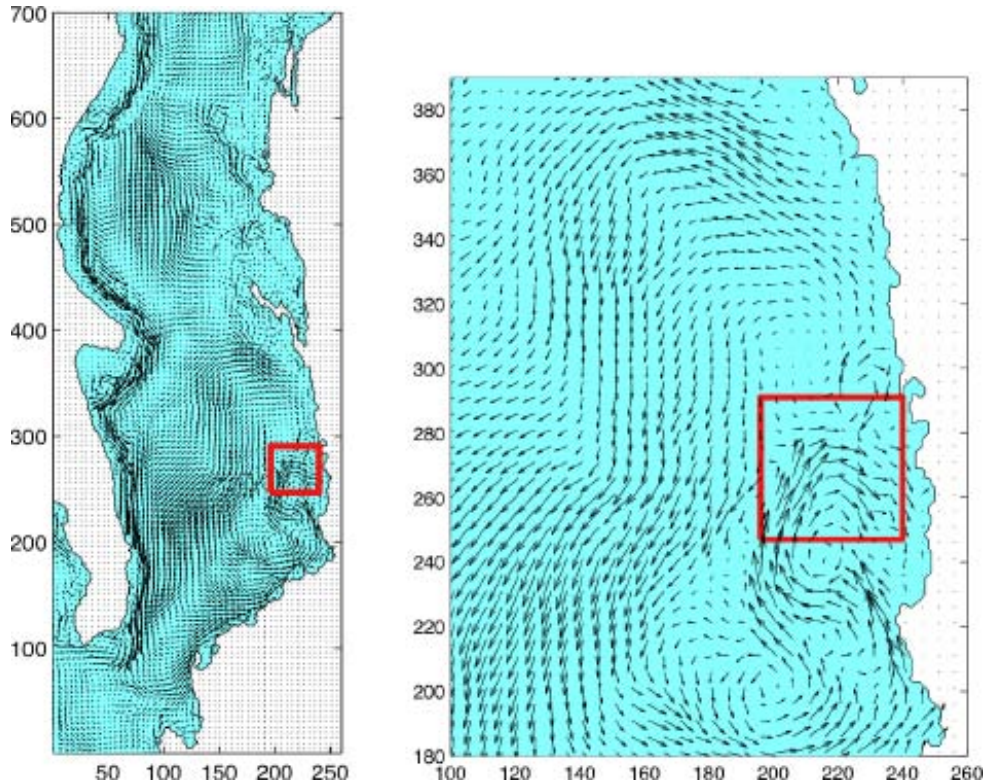


Figure 1: Snapshots of the surface velocity field produced by NCOM simulation of the Adriatic Sea. The left panel shows the location of the confinement region, marked in red, within the basin scale circulation. The right panel shows the details of the velocity field in the vicinity of the confinement region.

Our goal is to increase the residence times of a glider within the region given that the glider is subjected to drift prescribed by the model ocean currents. The left panel of Figure 2 shows the uncontrolled paths of Lagrangian drifters initially launched within the control region. The right panel shows the nominal residence times of uncontrolled trajectories as a function of the initial launch locations. The color bar indicates hours spent within the control region. The residence time is a strong function of nearby Lagrangian Coherent Structures and thus inherits an intricate dependence on initial conditions (x_0, t_0) . While there are large sets of uncontrolled trajectories that exit the region in less than 2 days, there are a number of trajectories that loiter for considerably longer times (up to 12 days). An essential element of the control strategy is based on maneuvering the AUV towards such nominal trajectories.

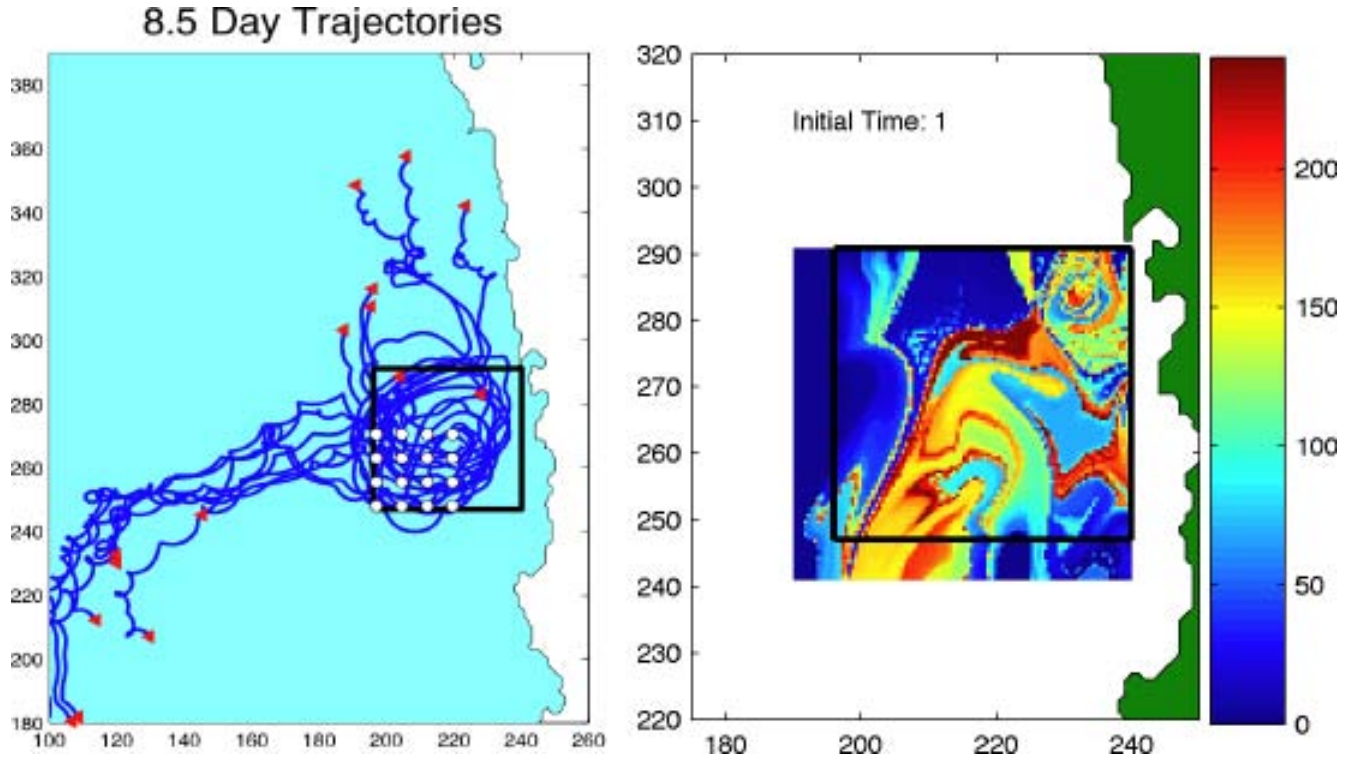


Figure 2: The left panel shows the 8.5 day evolution of 16 nominal, uncontrolled trajectories initially launched within the control region. The right panel shows a color-coded map of the residence time within the control region over an extended set of launch locations at a specific launch time. The color bar indicates hours spent within the control region.

Description of Methods

The optimal control approach taken is as follows:

- Identify nominal trajectories with large residence times. Such target trajectories need not necessarily be initialized within the control region.
- Solve the fixed final state/free final time optimal control problem to determine minimum time to a given target trajectory.

- Repeat for any number of simultaneous target trajectories.
- Find optimal feedback control over a distributed set of initial glider positions.

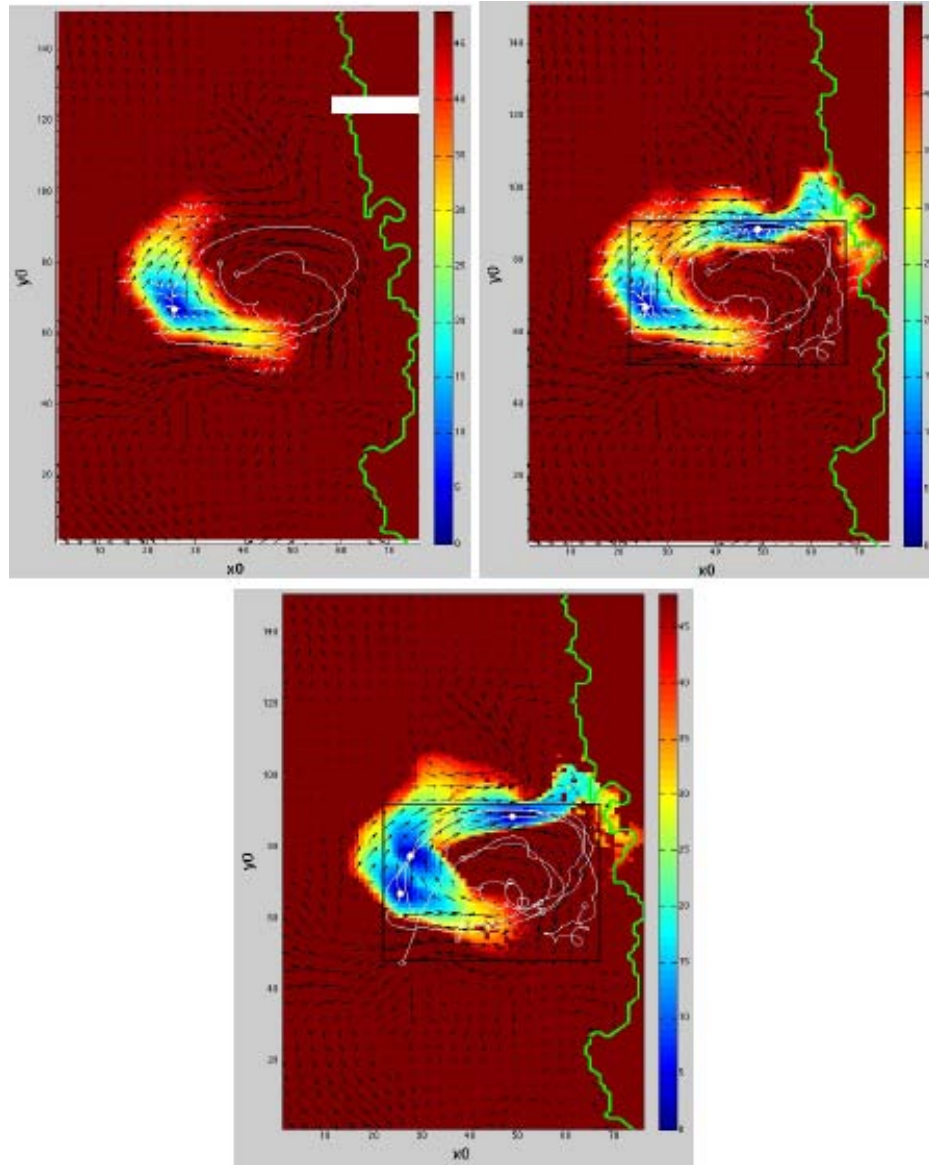


Figure 3: Single time snapshots of results of the control algorithm for a 48 hour simulation showing the extent of glider positions controllable to one (top left), two (top right) or three (bottom) distinct target trajectories. Nominal target trajectories are shown in white. The color scale indicates, as a function of initial glider position, the optimal time to target. Initial positions not controllable to any target trajectory within the simulation time are assigned a cost of 48 hours.

To solve the control problem, we implement an extremal field algorithm for numerically solving the minimum time problem for a vehicle moving with constant speed in a 2-D, time-varying numerical flow field. The result is the optimal feedback controller defined on a grid, along with the value function, or optimal cost function—the solution of the Hamilton Jacobi Bellman (HJB) partial differential equation.

The algorithm consists of two parts. First the Euler-Lagrange equations are integrated backward from some desired final state(s) and/or moving target(s) over a dense sampling of the (unknown) possible final costates. This generates a field of extremals in the 3-D space given by the 2 space dimensions and time. The 3-D field is then filtered to remove possible suboptimal extremal points leaving, at any initial time, a gridded field of optimal trajectories and their associated costs. Optimal feedback control can then be determined from the gridded cost-function. The algorithm can be adapted to handle general cost functions—e.g. combinations of time and energy, general bounded or unbounded velocity vector inputs, and general glider/ship models.

Sample snapshots in time of the results of the control algorithm run over a four-day time window are shown in Figure 3 for three different cases. Each plate shows the 10 day path of the nominal target trajectory (or trajectories) and quivers of the instantaneous model ocean velocity in black. The color scale indicates the calculated cost function, the minimum time to reach any target trajectory, as a function of initial glider position. The color scale is given in hours. Initial positions not controllable to any target trajectory within 48 hours are red. As can be readily seen in the figure, increasing the number of target trajectories increases the extent of controllable initial conditions and decreases the spatially averaged cost function.

Performance and Analysis

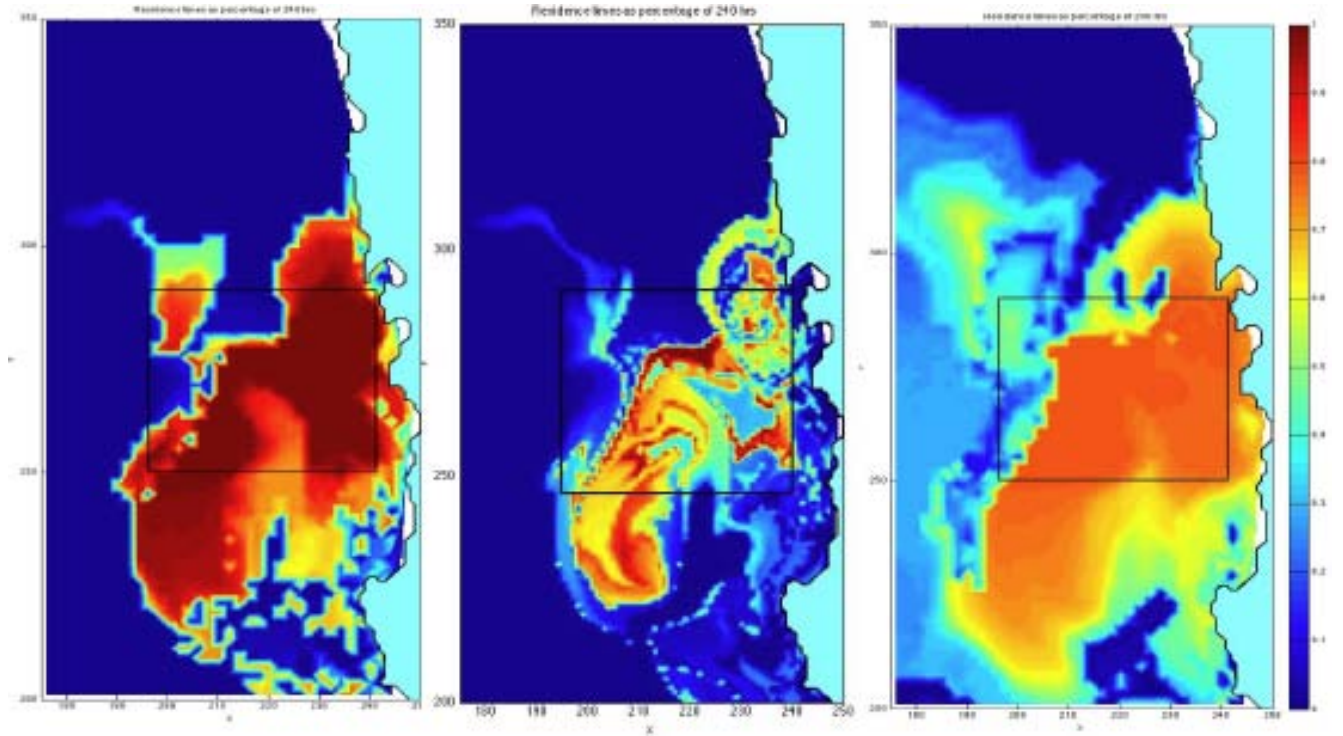


Figure 4: Comparison of distribution of localization times over initial glider locations for the NCOM Adriatic. Open-loop, central control dynamics shown in right panel, optimally controlled dynamics on left panel and no-control case in the middle. Both the number of initial glider positioned controllable to 10 day residence times and the residence times of given initial glider positions are markedly increased by the limited control which only acts for the first 48 hours. In both panels, the localization times are given as fractions of the 10 day window.

In Figure 4 we show the distribution of residence times over initial glider locations for the NCOM Adriatic. Open-loop controlled dynamics with glider trying to swim towards the center of the box shown in left panel, optimally controlled dynamics on left panel, and the nominal, no-control case in the middle. Both the number of initial glider positions controllable to 10 day residence times and the residence times of given initial glider positions are markedly increased (as evidenced by deep red regions in the right panel, that indicate gliders stay in the box for the full time-period) by the bounded optimal control algorithm which only acts for the first 48 hours. In all panels, the localization times are given as fractions of the 10 day window.

IMPACT/APPLICATIONS

The research conducted during the second full year of funding serves as a proof of concept for applying rigorous and objective optimal control theory to highly nonlinear, time-dependent numerical vector fields derived from ocean model output. The next goal is to extend the methods developed here for first order drifter dynamics to realistic second order models which explicitly account for the details of autonomous glider dynamics.

RELATED PROJECTS

This work is collaboration under the ONR PLUS effort with both Prof. I. Mezic' at the University of California Santa Barbara and Prof. I. Schwartz at NRL.

PI actively collaborates with Professors T. Ozgokmen and A. Griffa at the University of Miami on ONR funded research concerning Lagrangian data assimilation, optimal deployment strategies, model-data intercomparison and the sensitivity of Lagrangian Coherent Structure boundaries to model error and filtering. Similarly, the PI continues regular collaboration with Professors A.D. Kirwan and B. Lipphardt at the University of Delaware.